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Introduction into Spread Spectrum Technology

Article based on a Lecture at the Weinheim VHF-Convention 1982.

The spread spectrum technology is practically unknown to most radio amateurs although the theory has been known for fourty years. Spread spectrum technology is used in space technology and increasingly for military applications.

1. INTRODUCTION

Spread spectrum technology is a method of increasing the bandwidth of a radio frequency carrier beyond the bandwidth usually required for it to be transmitted. This may seem stupid for us radio amateurs who are always trying to keep the bandwidth as low as possible for reasons of sensitivity (CW, SSB) or limited frequency spectrum (narrow-band FM). Actually, the opposite method, the spreading of a modulated RF-carrier over the largest frequency range, really does possess a number of considerable advantages:

- Interference signal suppression (increased independence of interference of a two-way communication with respect to wanted or unwanted interference from other sources)
- Reduction of the spectrum energy density, thus less likely to be detected, and reduction of interference from other communication networks
- Secrecy of communications
- Accurate distance measurements.

Of course, these tasks that can be solved using spectrum technology, have already been solved using conventional methods. Interference freedom is usually encountered by increasing the output power; the identification of one's signal, or interference to third parties can be reduced by dropping the output power; the secrecy of the transmission is made with the aid of coding systems; interference and jamming transmitters can be avoided by using a number of previously arranged frequencies and/or previously arranged time intervals. All these methods are used by spread spectrum technology automatically.

The fundamentals of this technology were made in the USA before the Second World War by Shannon (2) as part of his studies regarding "Communications in the Presence of Noise" and was brought before the IRE (Institute of Radio Engineers) in 1940. The first publication of this work was delayed due to the war until 1947 (2). These ideas were not realized rapidly at that time since fast digital circuits, very wideband modulators, and modulation methods, as well as very wideband transmitters and receivers were required. In the fifties, one still had problems obtaining the required useful-modulation bandwidths and one was not able to imagine increasing these bandwidths by a power of ten. In the meantime, the US-military authorities, and several US-companies were working on research prototypes that covered the whole radio frequency range.
The real chance of realizing the spread spectrum technology was firstly to be seen in

the introduction of fast switching transistors from approximately 1960, and the use of integrated circuit technology from 1965. The military authorities in the USA recognized very quickly the value of this method for the realization of interference-free, and secure radio communications, and developed the first operational system.

The actual breakthrough for the spread spectrum technology was, however, not made in the military field, but in space and satellite technology. The Jet Propulsion Laboratory (JPL) of the NASA in Pasadena/California especially studied this method in the sixties for the design of communication methods for interplanetary missions that did not only provide a far higher data security of the information, but also allowed exact distance measurements to be made up to and in excess of the solar system. Nowadays, the various spread spectrum methods are "state-of-the-art" in space technology and are used in the military field for point-to-point telecommunications. This technology is still not used for military multichannel systems, or at least has not gone beyond prototype status.

Radio amateurs had their first contact with this method of communication relatively early in the research program. Costas (2) mentioned "Poisson, Shannon, and the Radio Amateur" in his fundamental IRE-publication of 1959. In this publication, he stated that an excessively full frequency band, such as the 40 m amateur band, could be arranged so that a considerably more effective channellization system can be provided with far more usable telecommunication channels with the aid of spread spectrum technology than could be achieved by using continuously decreasing bandwidths (the SSB-technology was just about to become popular in the shortwave range). However, the technical possibilities of this new technology were not available to radio amateurs at that time.

At the present time, experiments have already been made with the spread spectrum technology by radio amateurs. P.L. Rinaldo, W4RI, mentioned in a QST-article that the AMRAD (Amateur Radio Research and Development Corporation) intended to build up several experimental groups, apply for FCC authorizations, and carry out tests (4). In May 1981 (5) a limited authorization was given to AMRAD on several shortwave frequencies and for a larger number of experiments in the 70 cm band. Recommendations were then made to the FCC in December 1981 (6) to allow all extra class and advanced class licences to carry out spread spectrum experiments on the VHF and UHF bands.

As far as we know, no active experiments have been made by radio amateurs in the spread spectrum technology. However, quite a number of amateurs will suffer passively from such signals, since the AWACS early warning system will be using spred spectrum signals on the L-band (0.9–1.3 GHz), which will increase the overall noise level in the 23 cm amateur band by several dB.

2. FUNDAMENTALS OF THE SPREAD SPECTRUM TECHNOLOGY

The idea of increasing the security of a radio link using an artificially increased bandwidth is a direct result of the examinations made by Shannon (2) regarding the behaviour and the capacity of a telecommunication channel under interference conditions. Using several mathematical simplifications, it is possible for the relationships to be shown as follows:

The following basic magnitudes are used:

Power of the wanted transmitter	S [W]
Power of the interfering transmitter	J [W]
Bandwidth of the telecommunication channel	W [Hz]
Bit-rate of the information	R [Hz]

(for simplicity, binary signals are to be assumed, but the above considerations are just as valid for other analog signals)

The above allows the following magnitudes to be defined:

Power density of the interfering signal $N_o = \frac{J}{W} \left[\frac{W}{Hz}\right]$

Received energy per bit of the required signal $E_b = \frac{S}{R}$ [Ws]

The quotient E_b/N_o is without dimension and describes the signal-to-interference ratio and, according to Shannon, is inverse proportional to the bit error rate:

$$\frac{E_b}{N_o} = \frac{S \times W}{J \times R}$$

By rearranging this equation, it is possible for the "jamming margin" to be given; this is the ratio of interference power to signal power by which a certain bit error rate will be maintained:

$$\frac{J}{S} = \frac{\frac{W}{R}}{\frac{E_b}{N_o}} \quad \text{"Jamming margin"}$$

With conventional systems, the bandwidth W of the transmission channel is equal to the bit error rate of the information (e. g. for SSB), or a multiple of this for technical reasons (e. g. AM, DSB). This means that W/R is a constant and thus that the above equation is trivial; the jamming margin is determined by the signal-to-interference ratio.

The new idea of spread spectrum technology is that W/R should no longer be seen as a constant. It is permissible for the bandwidth W of the transmission channel to be artificially wide with respect to the minimum bandwidth determined by the bit error rate R of the information. As can be seen in the above equation, the jamming margin will increase linearly with the ratio W/R with a constant bit error rate.

$$G_p = \frac{W}{R} \quad \text{"Processing gain"}$$

The "processing gain" is very often given in logarithmic magnitude:

$$G_p' = 10 \log \frac{W}{R} \text{ [dB]}$$

For judging complete telecommunication systems, it is usually necessary to take the internal losses V_{sys}, as well as the signal-to-interference ratio V_D at the demodulator into consideration, by which a certain bit error rate is not exceeded. In this case, the jamming margin is calculated as follows:

$$\frac{J}{S} \text{(dB)} = G_p' \text{(dB)} - V_D' \text{(dB)} - V_{sys}' \text{(dB)}$$

An example is now to show which increase of the jamming margin is possible:

Information bandwidth:	5 kHz
HF-bandwidth (spread):	50 MHz
Processing gain: W/R = 10^4; G_p'	= 40 dB
Required S/N at demodulator: (e.g. PLL-RTTY demodulator)	+ 1 dB
System losses:	3 dB
Jamming reserve of the system:	36 dB

Due to the spreading of a narrow-band signal (5 kHz) to 50 MHz, the interference signal must be 36 dB stronger (approx. 5000 times) than the required signal (at the receiver input, in the passband range of the spread spectrum receiver), before the demodulation of the required signal is affected.

With the aid of this example, one can see which high spreading rates are usually required in order to obtain satisfactory processing gain values and why this was virtually impossible to obtain in the days of tube amplifiers.

3. SPREAD SPECTRUM PROCESS

The main requirement for realizing the spread spectrum technology are methods of spreading the RF-carrier over a sufficiently large bandwidth. The simplest form of a spread spectrum signal could be a wideband FM-signal with which the interfering signal suppression increases rapidly on increasing the frequency deviation. Such a FM-system should have a processing gain of $G_p \approx 3 \times M^2$ (M = modulation index). However, actual spread spectrum methods are only

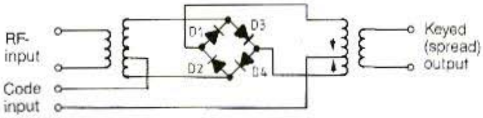


Fig 1:
Ring mixer as 0°/180° phase shifter

those by which the RF-carrier is not only modulated by the telecommunication signal, but with a further signal that is not used for communications but only for spreading.

Three main methods are used for this:

3.1. The direct sequence method (DS)

With images of the direct sequence method, the RF-carrier which may have been already modulated, can be increased in width by using a binary phase-shift keying with a certain, suitable binary code **(see Fig. 1)**. A balance mixer is used for the phase-shift keying, such as a four-diode ring mixer, where the IF-drive is made with a constant positive or negative voltage so that it is used as a 0°/180° phase-shifter. **Figure 2** shows the spectra of the individual signals more accurately.

The carrier to be spread is not modulated in our case, and therefore is shown in the frequency spectrum as a single spectral line. The impulse sequence used for spreading the signal has a line-type frequency spectrum whose envelope has the function of $(\frac{\sin \omega}{\omega})^2$. The zero positions correspond to multiples of the clock frequency.

The spectrum of the phase-shift carrier also has a line-spectrum with an envelope of $(\frac{\sin \omega}{\omega})^2$, which is located symmetrically around the original carrier frequency. In order to process this signal, it is usually sufficient for the frequency-band between the first zero points to the left and right of the center frequency to be used so that the minimum required bandwidth is identical with twice the clock frequency of the code sequence.

With sufficiently large spread bandwidths and suitable code sequences, (see Section 4) which have a virtually random character, the RF-power of the original carrier will be distributed virtually constantly over a wide frequency range, and the power density (W/Hz) will have a very low value. When received on a narrow-band (non-authorized) receiver, this signal will be heard as noise only, which will hardly change when tuning over a wider frequency range, and which can be so weak that it disappears into the interference and noise level. As can be seen, such transmissions are very secure and difficult to discover, and they will hardly ever cause interference to other telecommunication links using the same frequency range, due to their very low spectral power density. The prerequisite is, of course, a sufficiently high carrier suppression of the mixer, and good linearity of the amplifier so that the carrier is not regenerated due to intermodulation.

At the receive end, the phase-shift keying of the required carrier is demodulated using the same method (see **Figure 3**).

Of course, very many characteristics of the transmitted spread spectrum signal must be already known at the receive end (authorized receiver):

- The code sequence used for spreading
- The exact clock frequency of the spreading code
- The exact starting time of the code (phase position)

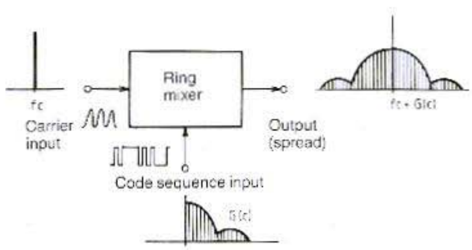


Fig. 2: Direct sequence method (DS); phase keying of a carrier using a PN-code

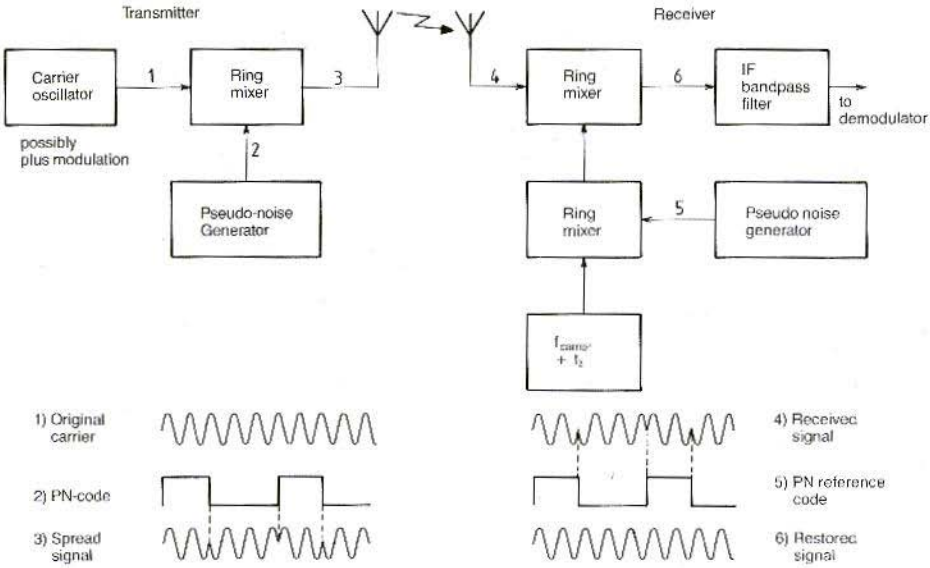


Fig. 3: Construction and operation of a direct sequence system

- The exact carrier frequency
  (It is advisable for carrier and clock frequency to be derived from a standard frequency oscillator at both ends using division or frequency synthesis).

The original, required modulated signal appears now at the output of the receiver-side phase-keyer (often called correlator), after which it can be fed to a conventional, narrow-band receiver for further processing and demodulation. Usually, the ring-mixer used as correlator also serves as first mixer by using an already spread RF-carrier that has been shifted to the value of the IF. The operation is not changed by this.

The behaviour of DS-spread spectrum communications with respect to narrow-band and wide-band interference, and the interference suppression that is achieved in this way is shown clearly in **Figure 4**.

The whole power contained in the spread spectrum signal is compressed in the correlator to a signal bandwidth that is suitable for processing in the subsequent receiver and demodulator. A narrow-band interference signal (such as a continuous carrier) will, on the other hand, be spread by the correlator in the same manner as the required signal in the transmitter, and only a fraction reduced by the value of the spreading factor (processing gain) will fall into the subsequent passband range. In addition to this, the interference signal appears at the output of the correlator as a quasi-noise signal, which means that the further processing in the IF-circuit will only cause a reduction of the signal-to-noise ratio and will not cause a correlated interference. Other wideband signals that are not correlated with the spreading code, will be further spread in the receiver correlator. This means that a far lower power density is present in the processing bandwidth than would be the case with narrow-band interference.

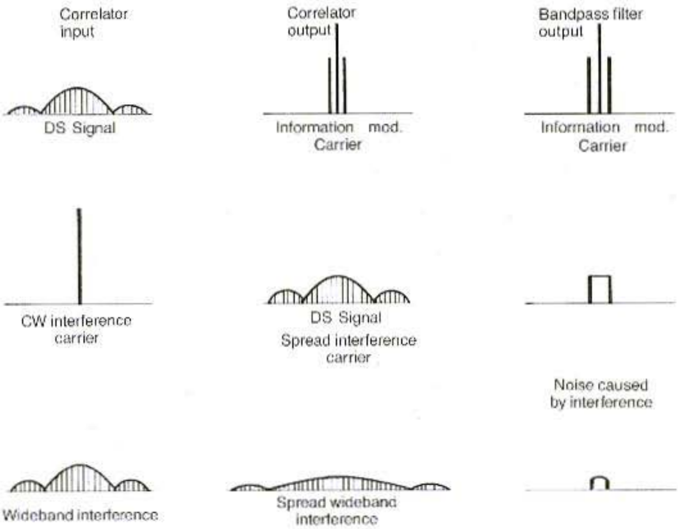


Fig. 4: Behaviour of a DS-system in the case of interference; narrow-band interference (cw), wideband interference (e. g. DS)

Such wideband interference can, for instance, be a second DS-spread spectrum signal having a different code, and this shows that a large number of DS-signals with a differing spread code can be accommodated in the same frequency spectrum. This method allows even a higher number of channels per frequency band than would be possible using conventional, narrowband systems since steep filter slopes, adjacent channel interference, multi-channel intermodulation, and the required safety spacings need not be taken into consideration in DS-systems.

A further advantage of such a channel distribution is that a DS-system is far less affected by overload conditions than a narrow-band channel system. In the case of the DS-system, only the signal-to-noise ratio of all channels will be reduced proportionally to the overload, whereas a narrow-band system will very soon become unusable under overload conditions.

3.2. The frequency hopping method (FH)

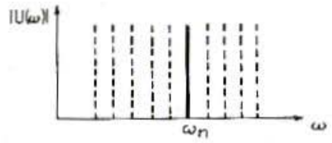
The second method of spreading the frequency spectrum of a transmit signal is to allow the carrier frequency to jump from one frequency to another by selecting one of a large number of available channels. The sequential selection of the frequencies is made according to a PN-code sequence, and will therefore appear to be random in a non-autorized receiver **(Fig. 5)**.

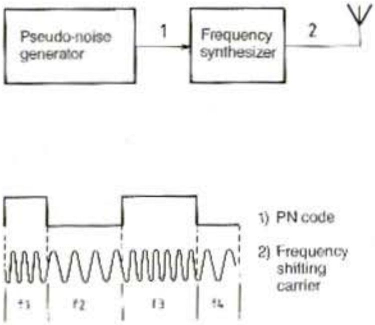
The autorized receiver controls its receive oscillator with the same PN-code sequence and will therefore follow the frequency hopping of the transmit frequency with the correct clock and phase.

This method can easily be realized with the present state-of-the art, and is naturally only possible since fast frequency synthesizers and the required programmable dividers, PLL-circuits and VCOs are available.

The frequency hopping (FH)-method also provides a processing gain in the same manner as with the DS-method. The theoretical gain $G_p = W/R$ was given here as the number N of the available channels:

$$G_p = \frac{W}{R} \rightarrow G_p\,(FH) = N$$





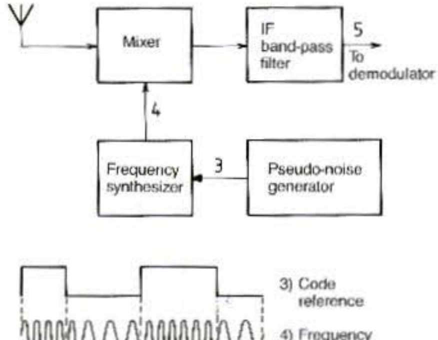


Fig. 5:
Frequency-hopping method
a) Frequency spectrum of a FH-system
b) Construction and operation of a FH-system

In the case of N = 1000 channels between which one jumps back and forth, the processing gain will be $G_p = 10^3$ or $G_p' = 30$ dB.

This can be seen easily in the following description, and digital modulation is again to be assumed for simplicity.

One channel is to be interfered with during these considerations, where the interference power should be greater than that of the required power. In a conventional narrow-band system, the error rate in this channel would then be = 1, or 100%. In the case of a FH-system, the error rate amounts to the following, if one data bit is transmitted per frequency jump:

$$p = \frac{\text{number of interfered channels}}{\text{number of available channels}} = \frac{J}{N}$$

A narrow-band interfering station with J = 1 would result in an error rate of $p = 1 \times 10^{-3}$ in the case of a 1000-channel FH-system with N = 1000. This is already a good value for voice communication; however, it is not sufficient for data transmission. For this reason, one has started to use more than one frequency jump per data bit (e.g. 3 per data bit), and to make a majority decision at the receive end (e.g. 2 from 3).

The possibility of errors can be considerably reduced in this manner. If 'c' represents the number of channels per bit, 'r' the required number of interfered channels in order to interfere with one bit, and 'p' the possibility of error for a normal FH-system, the new possibility of error P is as follows:

$$P = \sum_{x=r}^{c} \binom{c}{r} \times p^x \times (1-p)^{c-x}$$

In the above example with J = 1, N = 1000, $p = 1 \times 10^{-3}$, the possibility of error can be reduced to the following with c = 3 channels per bit and a decision of two from three:

$$P = \binom{3}{2} \times p^2 \times (1-p)^{3-2} = p^2 \times (3+p) \approx 3 \times 10^{-6}$$

3.3. The Chirp Method

The chirp method (pulse-FM) was mainly used in radar technology and not for telecommunications. However, it is also classed as one of the spread spectrum methods since the transmit spectrum is considerably spread using a special method. In order to complete our considerations, this is to be mentioned briefly in this article (**Figure 6**).

In the case of this method, the transmit frequency of a (radar) transmitter is continuously shifted during a keying time Δt by a frequency f_1 to a frequency f_2 (e.g. linearly with a sawtooth signal). The pulse transmit power is spread over the largest possible time range and frequency spectrum, and the mean power density will be reduced considerably. At the receive end, this frequency modulation is restored using a so-called dispersive filter with which the delay is dependent on the frequency. The power components of the different frequencies transmitted at differing times arrive simultaneously at the output; this means that a pulse compression occurs in the dispersive filter. This is a very useful effect for increasing the distance resolution of radar equipment.

In the case of a "compression ratio" $D = \Delta t \times \Delta f$, the signal-to-interference ratio will increase by $\sqrt{D}$, and the time resolution (= distance resolution) will be improved to $\Delta T = \Delta t / D$.

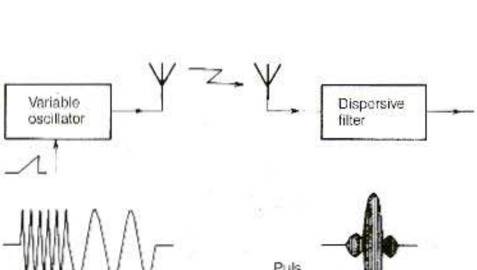


Fig. 6:
Chirp method (radar technology)

3.4. The Time-Hopping Method

In publications, the so-called time-hopping method is often classed as belonging to the spread spectrum methods, although, when used on its own, it does not offer hardly any advantages. The principle is that the telecommunication transmitter does not transmit continuously, but at certain time intervals that are determined by a PN-code sequence. This method also considerably widens the spectrum of a transmit signal. It is sometimes used together with a DS or FH-method and can improve the characteristics of these systems.

3.5. Combination of the Various Spread Spectrum Methods

Very often, several spread spectrum methods are used together in order to improve the system characteristics further, or to satisfy certain technical demands on a system with more simple means.

In the case of a combined DS/FH-system, the direct sequence and the frequency-hopping method are used simultaneously. The processing gain is equal to the product of the gains of the individual methods:

$$G_p^{tot.} = G_p^{(DS)} \times G_p^{(FH)} = \frac{W}{R} \times N$$

or logarithmically:

$$G_p'^{tot.} = G_p'^{(DS)} + G_p'^{(FH)} \text{ [dB]}$$

This combination is of interest when a certain processing gain cannot be obtained using a single method on its own, or only with difficulties.

If, for instance, a gain of 47 dB is required at a data rate of R = 10 kHz for interference suppression, it will be necessary to spread the signal over a bandwidth of W = 500 MHz in the case of a DS-system, which will require a PN-clock frequency of 250 MBit/s. In the case of a FH-system, it will be necessary to switch between 50000 channels. Both possibilities are at the limits of what is technically possible. If, on the other hand, the direct sequence and frequency-hopping method are combined, it is possible using a DS-code of 10 MBit/s and a

50-channel frequency-hopping system to obtain the required processing gain of 47 dB, and this is possible with normal means.

In spread spectrum communication networks with a multiple access, the DS or FH-method is often used together with the time-hopping method (TH). In this case, the individual stations only transmit at several time intervals, which are determined by a common PN-code. This allows one to achieve the condition that only one station is transmitting at any particular time. Even though spread spectrum signals can be operated quite well in the same frequency band, it is possible for local transmitters and receivers to be affected by unwanted desensitization.

4. CODING AND SYNCHRONIZATION

4.1. Code Characteristics

The demands made on a spread spectrum system can only be achieved when the spreading code possesses certain characteristics:

One-Zero Balance (High-Low Balance)

The number of 1 and 0 bits in a code should, if possible, be identical. This allows the DC-current component of the pulse sequence to be zero. The DC-component of a DS-system will cause the ring mixer to be switched through for a certain percentage of time which means that the original carrier will appear in the output spectrum in a noticeable manner (inferior carrier suppression). In the case of a FH-system, this would cause one channel to be used in preference to all others, and be accentuated in the output spectrum. In both cases, this will mean that the spectrum is no longer "noise-like", which means that the carrier can be recognized, can be interfered with, or can even interfere with itself.

One-Zero Distribution
(High-Low Distribution)

The distribution of the 1 and 0-bits within a code also has a large influence on whether the output spectrum appears "noise-like". The 1 – 0 distribution should therefore also be as statistic as possible, although it is, of course, generated using a predetermined method. This is often called "pseudo noise" (PN).

Low Code Repetition Rate

The frequency with which a "pseudo statistic" sequence of 1 and 0 bits repeats itself should not fall into the required information (modulation) frequency range, since this could cause interfering effects. Normally, it is placed below the lowest modulation frequency. Since, on the other hand, the clock frequency of the code must be very high, this results in very long codes.

Good Auto-Correlation Behaviour

The code must be arranged so that it can be identified well by the authorized receiver (auto-correlation). Attention must be paid that a similar code cannot cause a positive identification of the decoder circuit (even when they will be weaker).

Good Cross Correlation Behaviour

When fed into an identification circuit that compares it to another code (cross correlation), the received code should not produce an output signal. The auto and cross correlation behaviour of the codes will be discussed further.

4.2. Code Generation

The given demands are fulfilled by a number of so-called "maximum" codes. All other codes are called "non-maximum codes". The generation of such codes is made most easily using shift registers where the input of such a shift register is provided with the binary sum from the output signal, and the signal itself.

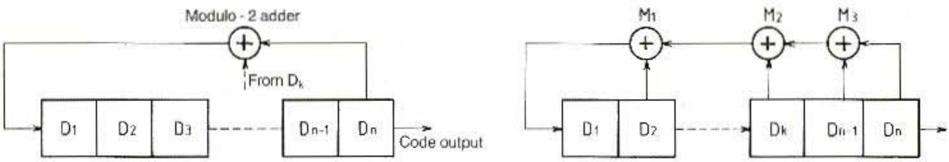


Fig. 7: PN-code generators using tapped registers

Due to the selection of the tapping point, various different codes can be generated (**Figure 7**).

Very often, several adders are used together with several tapping points, or combinations of signals from several shift-register generators. With the aid of microprocessor technology, it is possible for other methods and principles of generator circuits to be used for any required codes.

4.3. Auto-Correlation and Cross Correlation

In order to understand the receiver-end identification of the transmitted spread code, it is necessary to describe the terms "auto-correlation" and "cross correlation" in more detail. These correlation functions are a measure of the similarity of functions. In the case of the auto-correlation function

$$\varphi_A(\tau) = \int_{-\infty}^{+\infty} f(t) \times f(t-\tau)\, dt$$

a function f(t) (e.g. a time-dependent function such as sin ωt) is compared with itself, however, shifted by a magnitude τ (e.g. shifted in the time plane). This is achieved by multiplying all functional values with the associated values that have been shifted with the value of τ, and for all these products to be added (integrated) for all values of t. This function, of course, has its maximum at $\tau = 0$, which means that a function is most similar to itself without phase shifting. In the case of periodic functions, further maxima appear when τ is a multiple of the period.

The behaviour of the correlation function at other values than $\tau = 0$ determines how good the original function f(t) can be found again by variation of τ.

It is also possible using the same method to compare various functions f(t) and g(t) with the aid of the correlation function:

$$\varphi_K(\tau) = \int_{-\infty}^{+\infty} f(t) \times g(t-\tau)\, dt$$

This function is called cross correlation function. Since the functions to be compared are different, $\varphi_K(\tau)$ may never achieve the maximum value of $\varphi_A(\tau)$. The non-exceeding of a certain thresold is a sign that the functions are different.

In the case of the correlation of binary code sequences, the product in the above equations will obtain the value + 1, if the functional values coincide, and it is agreed that the value − 1 should be obtained (actually = 0), if they do not coincide. The integration then forms a summing of all bits of the code. The correlation value for a certain phase-shift can therefore be simply calculated by placing the bits over another and comparing then bit by bit. In this case, the correlation value is the sum of the coincidence or non-coincidence.

This is easily explained with the aid of an example. The maximum code sequence 1110010 is to be compared with itself in the seven possible phase shifts (**Figure 8**). The auto-correlation value is always − 1, except for the case of coincidence, where it is a maximum (number of elements). The amplitude of the maximum increases therefore with the length of the code, which improves the discrimination with respect to other codes (cross correlation).

Shift	Sequence	Agreements	Disagreements	A – D
1	0111001	3	4	– 1
2	1011100	3	4	– 1
3	0101110	3	4	– 1
4	0010111	3	4	– 1
5	1001011	3	4	– 1
6	1100101	3	4	– 1
0	1110010	7	0	7

Fig. 8:
Auto-correlation functions A–D for a maximum 7 Bit code

In the case of non-maximum codes, side maxima appear in the auto-correlation function (see **Figure 9**) and it is then important that a sufficiently large spacing exists between the main maximum and the side maxima at all times. Inspite of these disadvantages, non-maximum codes are often used, in order to exploit their advantages, as for instance their easier synchronization.

The time slope of the auto-correlation function is of special importance. The coincidence can be determined with an accuracy better than ±0.5 Bit. This allows one to determine the delay times of spread spectrum signals using the phase-shift, and thus to determine distances extremely accurately. At a code clock rate

Fig. 9a:
Auto-correlation function for a maximum code

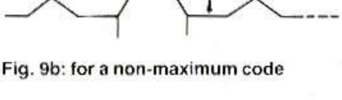


Fig. 9b: for a non-maximum code

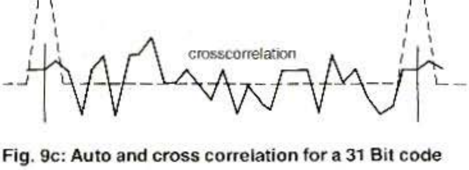


Fig. 9c: Auto and cross correlation for a 31 Bit code

of 100 MBit/s, it is possible to determine a distance resolution of better than 3 m!

The range of clear identification of the distance measurement is determined by the time-length of the code sequence. If this length is great enough, i.e. is always greater than, for instance, the duration of a space mission, this will mean that the distance measurement is always clearly defined. Which lengths are required for this and how many shift-register cells are necessary to generate it, can be seen in **Figure 10**.

One of the first large applications of spread spectrum technology was made due to this exact measuring possibility in the "Deep-Space Mission Program" of NASA.

The principle of the distance measurement is based on the measurement of the phase-shift of the comparison code on the receive end that is necessary in order to coincide with the originally transmitted code, and to result in maximum auto-correlation.

In many cases, it is not at all necessary for the receive end (e.g. space vehicle, satellite) to have its own spread spectrum installed. The whole spread spectrum signal can be converted to another frequency in a transponder and retransmitted to the transmit (ground) station. The evaluation can be carried out here much easier, since the spread code is already available, and no synchronization problems will appear.

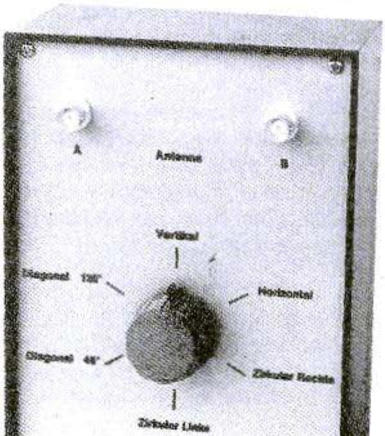
The same method is used for determining the distance of METEOSAT, as well as the distance of the new amateur radio satellite OSCAR 10 from the command station on the ground (7).

Register Length n	Sequence Length	Sequence Period
7	127	1.27×10^{-4} sec
8	255	2.55×10^{-4} sec
9	511	5.11×10^{-4} sec
10	1023	1.023×10^{-3} sec
11	2047	2.047×10^{-3} sec
12	4095	4.095×10^{-3} sec
13	8191	8.191×10^{-3} sec
17	131071	1.31×10^{-1} sec
19	524287	5.24×10^{-1} sec
23	8388607	8.388 sec
27	134217727	13.421 sec
31	2147483647	35.8 min
43	879609302207	101.8 days
61	2305843009213693951	7.3×10^{4} yr
89	618970019642690137449562111	1.95×10^{9} yr

Fig. 10: Code length and period duration at a bit rate of 1 MHz

To be concluded in edition 3/1984 of VHF COMMUNICATIONS.

FOR OSCAR 10 AND NORMAL COMMUNICATIONS



Polarisations Switching Unit for 2 m Crossed Yagis

Ready-to-operate as described in VHF-COMMUNICATIONS. Complete in cabinet with three BNC connectors. Especially designed for use with crossed yagis mounted as an "X", and fed with equal-length feeders. Following six polarisations can be selected: Vertical, horizontal, clockwise circular, anticlockwise circular, slant 45° and slant 135°.

VSWR:	max. 1.2
Power:	100 W carrier
Insertion loss:	0.1 to 0.3 dB
Phase error:	approx. 1°
Dimensions:	216 x 132 x 80 mm

UKWtechnik Terry D. Bittan · Jahnstr. 14 · Postfach 80 · D-8523 Baiersdorf
Tel.: West Germany 9133 / 855 · For representatives see cover page 2

Hans Ulrich Schmidt, DJ6TA

Introduction into Spread Spectrum Technology

Article based on a Lecture at the Weinheim VHF-Convention 1982.

Second, concluding part

4.4. Synchronization

One of the greatest problems in spread spectrum technology is the synchronization between transmitter and receiver. The method obtains its enormous processing gain, of course, from the fact that practically everything is known about the transmit signal at the receive end, with the exception of the actual information itself.

For this reason, the receiver must know the following values exactly, in addition to the exact transmit frequency, in order to decode the transmit signal:

- The spread code sequence,
- the clock rate of the code sequence
- the commencement time of the code sequence (phase shift) to an accuracy of ±0.5 Bit.

In this case, one considers a synchronous condition. The synchronization must be maintained under all conditions, such as doubler shift ("tracking").

Three methods are usually used to fulfill these demands:

- Transmission of the reference code by the transmitter
- Frequency and phase synchronization using a standard frequency transmitter
- Synchronization by only evaluating the spread spectrum signal.

In the case of the method that transmits the reference signal **(Figure 11)**, virtually all synchronization problems have been solved.

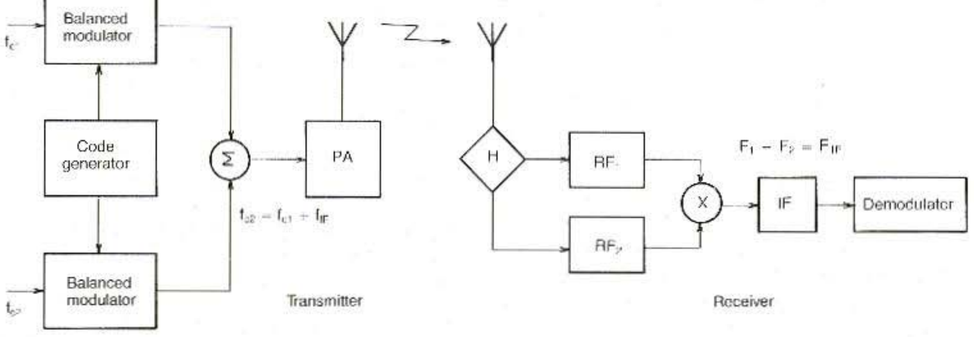


Fig. 11: Synchronization method using a transmitted reference signal

For this reason, the first experiments with spread spectrum technology were carried out in this manner. In this case, a modulated carrier f_1 is spread with the aid of a PN-code and transmitted, and an unmodulated carrier f_2 is also spread using the same code, and transmitted simultaneously.

At the receive end, both signals are received and fed to the two RF-inputs of a mixer. The unmodulated, spread carrier is now used as receive oscillator for the modulated one, and the intermediate frequency $f_2 - f_1$ will appear unspread at the IF-output of the mixer used as correlator.

This method can be used both with DS and FH-signals and is possibly the simplest method for radio amateurs for such communications in the microwave bands. Naturally, the security of the transmission will suffer, if it is received on a non-authorized receiver, since the transmitted reference and its frequency spacing can be determined.

In the case of the second method, all transmit and clock frequencies at both ends of the transmission link are derived from the signal of a standard frequency and time transmitter (e.g. DCF77WWV). As unknown constant, there only remains the phase shift due to the distance between transmitter, receiver, and standard frequency transmitter, as well as any possible phase response due to propagation.

As long as the stations are not mobile, and defined propagation conditions exist without variations in reflection and deflection, it should be possible for a manual adjustment of the phase shift to be sufficient for preliminary experiments. If this is not the case, it is necessary for the required phase shift to be forecast using doubler measurements made on the standard frequency, or to be compensated for using a phase synchronization.

If the transmitter and receiver can not be synchronized with the aid of a third signal, extremely high demands are placed on the frequency stability of the RF-systems, and automatic phase synchronization circuits will be necessary in all cases.

These circuits comprise a detector that measures the auto-correlation value at the output of the correlator (e.g. IF-output voltage of the receiver) as a function of the phase shift, a phase-shifter for the PN-code sequence that is controlled by the detector signal, as well as amplifiers and low or bandbass filters that form a phase control loop. In the case of the simplest FH-systems, the detector evaluates only the amplitude, and sophisticated demodulators evaluate the auto-correlation function according to amplitude and phase.

At the commencement of a synchronization process, it is necessary for the phase to firstly lock-in. This is achieved by shifting the phase of the receiver code sequence with respect to the transmit phase continuously, or in steps, until coincidence is achieved, which is when the output amplitude of the correlator is maximum (shift correlator). Since the shifting can only be carried out very slowly with respect to the code clock sequence, very long search times result with the long codes required for data security.

The length of the codes used for distance measurements will not allow this search process. These problems can be solved by using shorter codes that are only used for synchronization, or synchronization to parts of the codes in non-maximum code sequences. The disadvantage of such short synchronization codes is, however, the loss of interference signal suppression in comparison to that existing under synchronized conditions.

It would exceed the range of this article to discuss this in more detail and to discuss specific synchronization circuits. The greatest number of articles published during recent years have been discussing this problem of spread spectrum technology.

5. SPREAD SPECTRUM TECHNOLOGY AND APPLICATIONS

This article has shown that the spread spectrum technology possesses a number of tech-

nical characteristics that allow conventional telecommunications to be improved when used individually or as a combination.

The high security due to the low spectral power density, and the **high rejection of interference** have made the spread spectrum technology mainly interesting for military communications. For this reason, there are already a large number of military ground-to-satellite and ground-to-air communications, as well as missile control systems that are based on this technology, which are very difficult to jam with any electronic counter measures (ECM) available. One example described in (2) is the ground-to-air communication of the AWACS reconnaissance aircraft. They operate a DS-system over the whole of the L-band (915 – 1215 MHz) with a data rate of R = 56 kHz and a spread bandwidth of W = 300 MHz. This corresponds to a processing gain of $G_p' = 37$ dB. In addition to the high rejection to jamming, the use of an occupied frequency band is decisive.

The British manufacturer RACAL has developed a frequency-hopping system for tactical VHF-communications in the range of 30 to 88 MHz. In this case, frequency hopping is made between a total of 2320 channels ($G_p' =$ 34 dB). Due to the highly integrated circuits used in this equipment, these stations are not larger than a conventional VHF-transceiver, and this system can be used for portable and mobile communications.

In addition to the security against willful jamming, spread spectrum technology can also be used for the suppression of propagation-dependent interference. For instance, the interference due to multipath propagation (delay effects) can be eliminated well in the case of VHF/SHF over-the-horizon communications (Troposcatter). It is also possible for it to be used in the shortwave range (selective fading), however, the characteristics of the ionosphere limit the spread bandwidth. Quite recently, this technology has been used for experiments on carrier-frequency transmission systems on power lines, where great improvements are expected over existing systems.

A very interesting aspect, even for radio amateurs, is the most **effective use of the frequency spectrum**, and the possibility of **multiple use of frequency bands.** As has been mentioned previously, it is possible for the same frequency range to be used by a number of spread spectrum communication links using different codes, and more systems can be accommodated than when using conventional narrow-band systems. Furthermore, these transmissions can be used together with conventional systems, which means that already occupied frequency bands can be used "once again".

In the example of the AWACS aircraft, this has already been realized; in this case, the DS-system is operating in the same frequency range as the TACAN and IFF-equipment of military aircraft, and the DME and transponder of civil aircraft. In the USA, recommendations have been made and experiments are being carried out to use the, relatively speaking, enormously wide TV-bands for additional spread spectrum communications. This could solve the problems of VHF-mobile communications. There are already plans to reorganize the complete mobile telecommunication system based on spread spectrum technology and for it to be redistributed.

It is also possible for additional channels to be obtained in carrier-frequency systems on cable and microwave networks. Measuring equipment is available on the market that allows measurements to be made on fully operational systems using spread spectrum signals.

Further advantages of the spread spectrum technology result from the possibility of **multiple access** to telecommunication networks and from the addressability. In the case of a code multiplex system, it is possible to simultaneously transmit to all stations, and for confidential transmissions to be made between individual stations of the network. In this case, individual stations are addressed with the aid of a certain PN-code. Recommendations already exist for car-telephone, mobile communications, and automatic perimetry systems.

Another very important characteristic is the possibility of carrying out **exact distance measurements** with the aid of spread spectrum signals. Interplanetary space flights are unthinkable without this technology, as are the orbital parameter measurements of satellites (OSCAR 10), as well as the satellite navigation systems for aeronautical and marine use.

6. RADIO AMATEUR APPLICATIONS

As can be seen in US-American radio amateur publications (4 – 6), one is becoming more and more interested in this new transmission technology, and it is in the interest of the experimental nature of amateur radio that radio amateurs should experiment with this. In addition to the general interest in this technology, it is also possible for it to be used in the future for new band-plans for repeater stations, VHF-communication channels, linear transponders, and for amateur satellite communications. In the shortwave range, it is possible for interference caused by the overfilled frequency bands and unauthorized transmissions to be solved with the aid of a frequency-hopping system. Since personal computers are becoming more and more popular, it would be possible for even code multiplex communication networks with addressable stations to be built up on the UHF/SHF-bands, and the "package radio"-experiments of American radio amateurs are a first step in this direction.

After considering all these new "wideband" ideas, one might get the false impression that all previously used narrow-band systems are suddenly obsolete. The opposite is the case, since the new technology obtains its processing gain partly in that the receiver portion subsequent to the correlator carries out a very narrow-band processing of the signal.

The signal-to-noise ratio of this part, and thus the whole processing gain can still be improved by a further reduction of the IF-bandwidth (for example: using matched filters, synchronous demodulation etc.).

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